Large Scale 3D Printing with Cable-Driven Parallel Robots

Jean-Baptiste Izard*✉, Alexandre Dubor#, Pierre-Elie Hervé*, Edouard Cabay#, David Culla¤, Mariola Rodriguez¤, Mikel Barrado¤

*Tecnalia France, 950 rue Saint-Priest, 34070 Montpellier, France

#Institute of Advanced Architecture of Catalonia, Pujades 102, 08005 Barcelona, Spain

¤Tecnalia, Paseo Mikeletegi 2/7 - Parque Tecnológico, E-20009 San Sebastián, Spain

Corresponding author:
Jean-Baptiste Izard
e-mail: jeanbaptiste.izard@tecnalia.com
tel: +33 467 107 130

Abstract

Gantry robots and anthropomorphic arms of various sizes have already been studied and, while they are in use in some parts of the world for automated construction, a new kind of wide workspace machinery, cable-driven parallel robots (CDPR), has emerged. These robots are capable of automated movement in a very wide workspace, using cables reeled in and out by winches as actuation members; the other elements being easily stacked for easy relocation and reconfiguration, which is critical for on-site construction. The motivation of this paper is to showcase the potential of a CDPR operating solely on motor position sensors and showing limited collisions from the cables for large scale applications in the building industry relevant for additive manufacturing, without risk of collisions between the cables and the building.

The combination of the Cogiro CDPR (Tecnalia, LIRMM-CNRS, 2010) with the extruder and material of the Pylos project (IAAC, 2013), open the opportunity to a 3D printing machine with a workspace of 13.6×9.4×3.3m. The design patterns for printing on such a large scale are disclosed, as well as the modifications that were necessary for both the Cogiro robot and Pylos extruder and material. Two prints,

✉ e-mail: jeanbaptiste.izard@tecnalia.com - tel: +33 467 107 130
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with different patterns, have been achieved with the Pylos extruder mounted on Cogiro: the first spanning 3.5m in length, the second, reaching a height of 0.86m.

Based on this initial experiment, plans for building larger parts and buildings are discussed, as well as other possible applications for CDPRs in construction, such as the manipulation of assembly processes (windows, lintels, beams, floor elements, curtain wall modules, etc.) or brick laying.

Keywords: Additive Manufacturing, Cable-Driven Parallel Robots, Innovative Construction, On-Site Digital Fabrication, Parametric Design, Periodic Continuous Line.

Introduction

While architectural practice and the building industry has been traditionally slow to integrate technology, digital fabrication, 3D printing and robotics are gaining in momentum towards designer and architects. While highly precise element can be prefabricated in off-site factories (such as curtain wall and CNC machined structures), the building still mostly consists in on-site assembled parts. Technical, economic and environmental costs are therefore increased. In this regard, bringing the fabrication on-site would greatly reduce these costs as well as many limitations. In this regard, digital fabrication and additive manufacturing technologies (such as 3D printing on site) are being gradually introduced by the first researchers and architectural practitioners [1, 2], finding synergies between their "business as usual" practices and additive manufacturing (AM). For example, CAD software used by architects is also used in AM to design complex geometries, with the possibility of optimizing shapes and material distribution, as well as having the potential to create them quickly and with precision. While AM for architecture is yet at an early stage, a clear potential have been identified by industries, contractors and architects to reduce the cost of customized fabrication, and therefore create a change of paradigm from the twentieth century standardized architecture of mass production toward the contemporary digital architecture of mass customization and site specific adaptation [3].

Today, 3D printing is used predominantly to produce small scale objects, with processes adapted to this use. Scaling up these processes, in order to reach the dimensions of structural elements and buildings, creates a series of issues: one problem faced by large-scale 3D printing is size and configuration of positioning devices and their machine elements. CNC routers and robotic arms are predominantly used in AM as print head positioning devices. To scale up the range of said positioners, the most common approach is to use cartesian robotic systems, that ensure positioning in 3 dimensions throughout a workspace only depending on the dimensions of the supporting beams and rails. This is the approach elected for contour crafting [4] and by DShape [1]. WASP team [5] has chosen to extend the dimensions of a linear delta robot design to reach a cylindrical workspace measuring 6m in diameter and height. However, scaling up such devices implies problems for installation in constrained building sites as well as high costs of machine transportation, in particular in the case of Cartesian robots, which require heavy supporting beams, typically larger than the workspace. It also brings forward the question of achieving millimetric movements over very large spans of workspace, ranging tens of meters, while maintaining operational costs low, and limiting the number of sensors required for the operation of the machine.

AM for architectural purposes has however made great progress recently through the use of robotic devices, and in particular anthropomorphic robots. They do qualify for off-site fabrication of structural elements [6, 7]. Commercial solutions already exist for on-site brick-laying machines [8, 9]. These solutions require advanced sensing techniques that compensate deviations (sway, vibrations, wheel slip and imprecision) and operate in a precise manner.

Recent developments on large workspace machinery, in particular cable-driven parallel robots (CDPR), provide new solutions for AM for construction purposes. A CDPR is in its essence a set of at least 6 cables, reeled in and out by winches, which connect together a frame and a platform. Through setting the length of the different cables in a synchronous way, the load can be steadily moved in a wide portion of the footprint, with control and stability in all 6 degrees of freedom (DOF). CDPRs are foreseen in various applications: very large workspace positioning of systems such as aerial cameras [10] and radio telescope receiver [11], emergency deployable robots [12, 13] or service robotics [13]. Construction uses have been foreseen as well, through concepts for façade inspection [14] and real-world demonstration for workshop applications [15, 16]. These already pave the way for use of CDPRs in pick and place like tasks, such as brick laying or curtain wall assembly, with or without human assistance.

Bosscher et al. [17] have pushed forward the idea of performing contour crafting [4] through a conceptual design of a CDPR. The platform with the printing head is moved by the synchronous movement of 12 cables, 4 of them being drawn upwards, 8 downwards, leading to a so-called *overconstrained* design. The drawing points of the 8 lower cables are raised as construction carries on. The paper provides technical analysis of the robot workspace in various states of construction, as well as economic analysis of the process.

Barnett and Gosselin [18] have been first to demonstrate 3D printing with a CDPR. The provided design is so-called *suspended*, meaning that all cables are drawn upwards from the platform, leaving the work area collision free. The workspace represents 33% of the footprint, a hexagon 1.22m in side. The 3D printing process is two-material wire deposition for structure and support. The paper showcased fabrication of complex geometry and scaled up sculpture replica, with the help of a sensor to ensure accuracy.

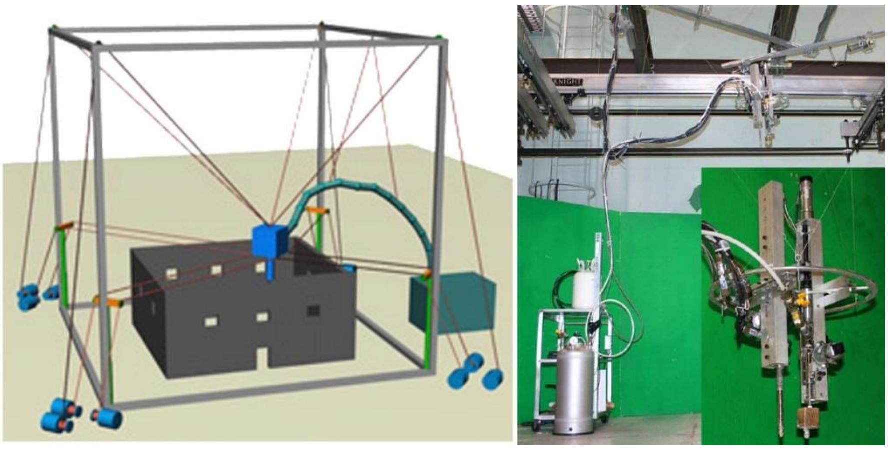

Fig. 1. Contour crafting overconstrained CDPR (◄, [12]); foam printer suspended CDPR (►, [18]).

A CDPR can be designed to be transportable, with its longest elements being cables that may be reeled; the frame may be built in several posts fixed to the ground, which may be easily displaced and rearranged individually. Suspended architectures allow for avoiding clashes from the cables. Due to the parallel nature of its kinematics, errors from the different degrees of freedom do not stack up; this feature paves the way for accurate positioning even for large workspaces spanning tens of meters, without the need of additional sensing equipment which are typically expensive for this kind of requirements, provided modelling of cables is sufficiently precise [19].

The motivation of this paper is to determine whether a CDPR is suitable for AM for construction without having to add any external sensor to the system. A test campaign has been set up to operate together Pylos [20] and Cogiro [21]. First section in the paper discusses the various modifications carried out in order to print in large dimensions with the CDPR. A second section showcases the different results from the experiments. A last section discusses the expectations based on these results.

Combining Cogiro and Pylos

Pylos is the result of a research action at IAAC on large scale AM processes, using material with low ecological impact, 100% natural and biodegradable, for architecture. The material is a soil based mixture with natural additive specially tailored for AM with an improved tensile strength and viscosity. The extruder developed is composed of a canister with 15L of capacity for the material, compressed by a pneumatic cylinder. The extruder measures 0.3×0.3×2m. It allows printing with a layer thickness between 1 and 7mm, 6 to 30mm in width, at a speed between 0.05 and 1m/s.

Cogiro is a suspended CDPR owned by Tecnalia and CNRS-LIRMM [22]. Its original point of design resides in the way the cables are connected to the frame, which makes it a very stable design [21]. It features a footprint of 15×11m, 6m high, and is capable of holding a load up to 500kg over more than 80% of the footprint. Advances in robot control have allowed to reach repeatability in the millimetric range and precision in the low centimetric range [19]. Several demonstrations of industrial scenarios have already been run using Cogiro [16, 22] in order to show the versatility of the CDPR concept.

Mounting Pylos on Cogiro

The whole platform together with the extruder filled with clay weighs between 157kg empty and 169kg filled up. The extruder is controlled by an output of the controller of the CDPR.

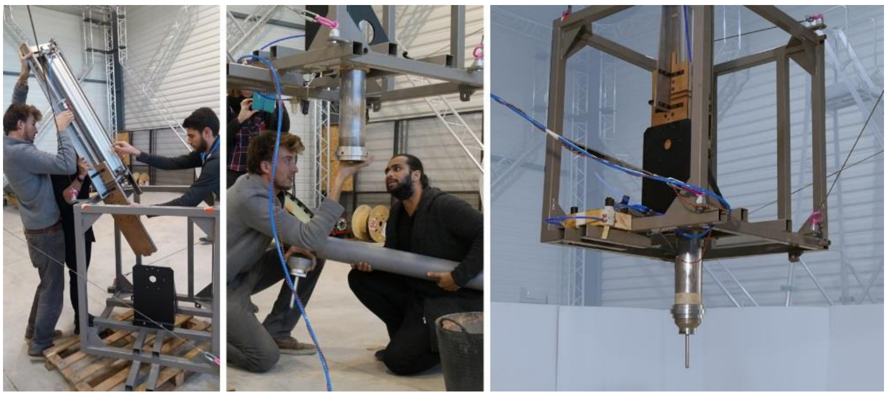

Fig. 2. Assembly of Pylos extruder on Cogiro.

With this payload, Cogiro is capable of moving the tip of the extruder with the platform in upright position inside a rectangle measuring 13.5x9.4m (77% of the footprint), and up to 3.36m above the floor.

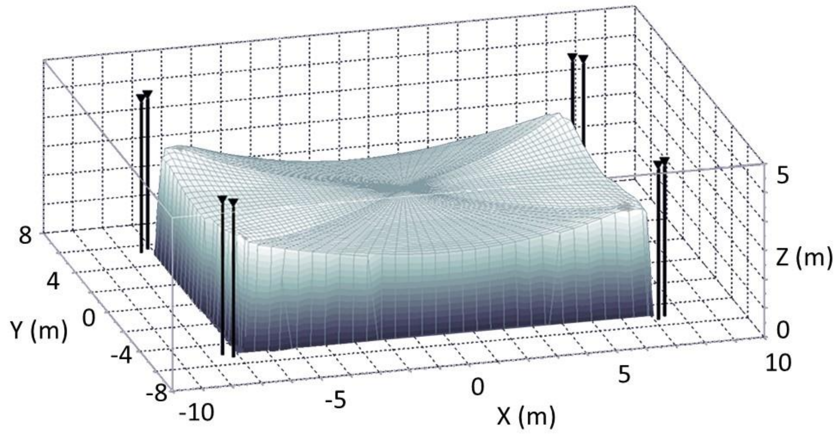

Fig. 3. Wrench-closure workspace of Cogiro with Pylos extruder mounted. Black triangles indicate the drawing points. Coordinates indicate the position of the tip of the extruder.

The original design of the Pylos extruder has been modified for its use on the CDPR: a system of rechargeable canisters has been developed, through which the piston pushes the material.

Trajectory control of the CDPR

In order for Cogiro to follow precisely the trajectories, a G-Code postprocessor module has been integrated, based on CNC modules on the B&R software and hardware of the CDPR, running on Automation Studio 4.

Trajectories are designed using Rhinoceros 3D and a custom script crafted by IAAC with Grasshopper 3D. This script computes the optimal path of the CDPR much like a CAM software. The output of the script is a G-Code file with position and printing speed instructions for following the desired trajectory within a deviation of 2mm.

Curvature appeared as an important feature of the trajectory for printing with a CDPR. Preliminary tests on Cogiro have shown that at the desired printing speed (0.15m/s) the local radius of curvature should not be lower than 25mm. Undesired vibrations show up when this limit is exceeded. When a smaller radius is required, the printing speed is brought lower to limit the acceleration from the trajectory. At the end of each layer, the robot is programmed to make a start and stop at the finishing point of the current layer and the starting point of the coming layer.

Tests carried out with Pylos and Cogiro

Preliminary tests

First tests have been run using common clay paste for modelling [23, 24, 25]. The material is fairly weak and shows high shrinkage during the drying process (>6%) because of high water content. Performance was enough to make the first tests with the pattern generator and test different parameters on the CDPR, in particular printing speed, versus precision of the print.

The first test was printing polylines in order to see the constituency of the robot to follow a rectilinear trajectory, and test layer stacking. The CDPR behaved well at the tested speeds (up to 0.2m/s) in that the trajectory stays linear along a line of 1m in length and the altitude keeps constant so that the layer thickness is homogeneous at 3mm, and the layer width is also constant at 11mm. When printing in layers, they overlap precisely, showing good repeatability in trajectories of the CDPR, even when dealing with small dimensions with regard to the size of the workspace (some millimeters versus about ten meters). Severe unwanted accumulation of material take shape at the lines start and stop points, even though stop time is nonexistent.

The second test involved a curved trajectory serving as the pattern for a curved wall. The pattern is 1m long and 0.20m wide with the shape of a sinusoid. The radius of curvature at apexes is 25mm. Some layers have been printed first with different speeds, ranging from 0.2m/s to 0.1m/s. At 0.2m/s, because of the curvature of the trajectory, oscillations have occurred that deviate the print from its trajectory by up to 4mm but that also result in a non-homogeneous width, which is the result of vertical oscillations estimated at +/-1mm. At 0.15m/s, oscillations in the horizontal plane are still present but with acceptable amplitude (<4mm), and the width of the print does not reveal any significant oscillations in the vertical direction. At 0.1m/s, oscillations are limited.

Fig. 4. Test preliminary prints at different feed speeds.

Subsequently a short wall has been printed with this pattern. The width of the pattern is reduced as height increases. Height reached 0.25m; it has been stopped as the material proved too weak in its wet condition for the structure to go further up.

Fig. 5. Test structure.

Long wall print and pattern test

After printing, the material contracts while drying; depending on the geometry and length, the material might break or crack. Cracking occurs on a straight line if it exceeds 16cm in length. Additionally, a straight line will contract in one direction, while a curved line will contract in two directions, absorbing its deformation and limiting breakage. With minimum radius of 25mm given as a limitation of the CDPR, a first prototype was printed: 20cm wide and 3.5m long (Fig. 6.). In this print, while the overall geometry appears as a straight line, it is actually a series of straight segments of 16cm linked by a small curved line of 25mm, enabling material retractation without breakage.

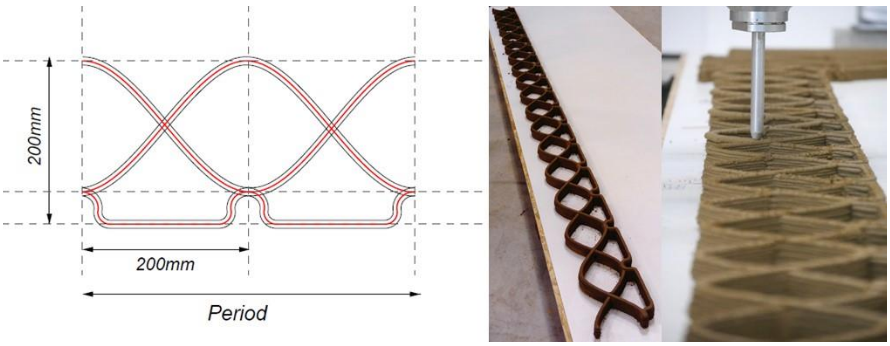

Fig. 6. Long wall print.

A set of additional pattern designs have been printed for testing (Fig. 7.). A drying process using IR lamps has been tested on portions of the print. The drying test gave important indications on the relation between design and material shrinkage, especially on such a long length. The results emphasized the need to keep unsupported straight wall under 16 cm, while exhibiting that the weakest point of the structure lie at the intersection of lines. Connection between lines appeared to be stronger if replaced by touching lines without overlap.

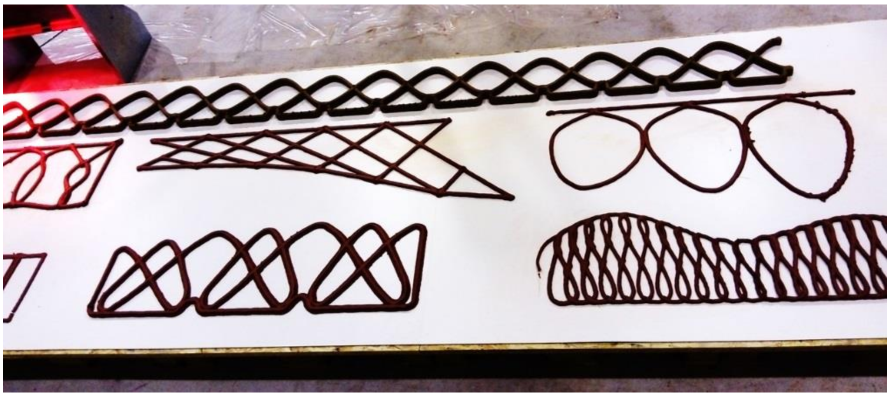

Fig. 7. Test on different patterns.

Due to large dimensions involved, CDPR technology leads to increasing printing scale drastically. However, two lines that intersect or overlap ought to be wet in order to bond structurally. Besides, if we consider a printed wall consisting of 5 layers of material, the printing path needs to privilege completing the full width wall printing, to make sure two consecutive layers are printed while still wet, rather than travelling back and forth along the length of the part.

High print

Respecting this strategy, parametric design has been implemented with a condensed periodical pattern without self-intersection. It features a straight face for the internal wall finish, a dense infill for structural performance, a ventilated infill for thermal performance, and a curved face exposed to the exterior for solar performance. The printed piece consists in two periods of 38.6cm long by 41.5 cm wide each, which could be extended endlessly (Fig. 8.), and targeted 1.5m in height.

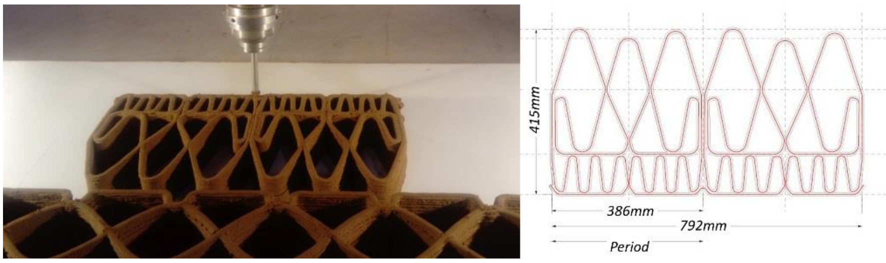

Fig. 8. Pattern for the high print.

As the part was getting printed, it appeared that the unloading of the clay from one canister was generating a steady vertical shift of about +5mm due to the sensitivity to payload of a CDPR. This made every stack of layers printed by a single canister 5mm thicker than it should be. Several mitigation solutions could have been applied: modify the weight input of the control of the CDPR in function of time for the control to compensate for the weight loss; or use adaptive control [26] in order to compensate automatically such changes in the model.

Fig. 9. Cogiro, Pylos and the high print being processed.

On the last day of this experiment, after an intensive day of continuous printing, stacking over 60cm of uncured material, bulking have been observed on the front section of the wall.

This experience revealed the need to better consider the drying time of the material and the structural capacity of the uncured material in the printing process. Without necessarily changing the material, altering the design and favoring horizontal distribution instead of vertical concentration of uncured material would provide better results. A vertical growth limit of 20 cm per day seems to be suitable to this process and material. Both techniques would require further testing for qualifying to solve the encountered issues.

At higher levels of print, the quality of the level of the layers had degraded. Positioning errors have been witnessed, leading to uneven thickness and width of the material layer. These errors are the result of the design of the controller, operating in joint space with dual-space feedforward [26], combined with low reduction ratio on the motors. In order to visualize this phenomenon, a test campaign on the CDPR moving along a sample printing trajectory without performing extrusion at different altitudes the has been performed to visualize which positioning error of the CDPR leads to which layer quality. Cartesian errors discussed further are reconstructed from joint errors measured at motor encoders using the local small displacement Jacobian matrix.

Horizontal errors appear independent to altitude of print and are kept within ±4mm, meaning that the wire of the layers overlap correctly given their width of 11mm. Vertical positioning errors, pictured on Fig. 10, appear therefore as the reason of the degradation of layer quality.

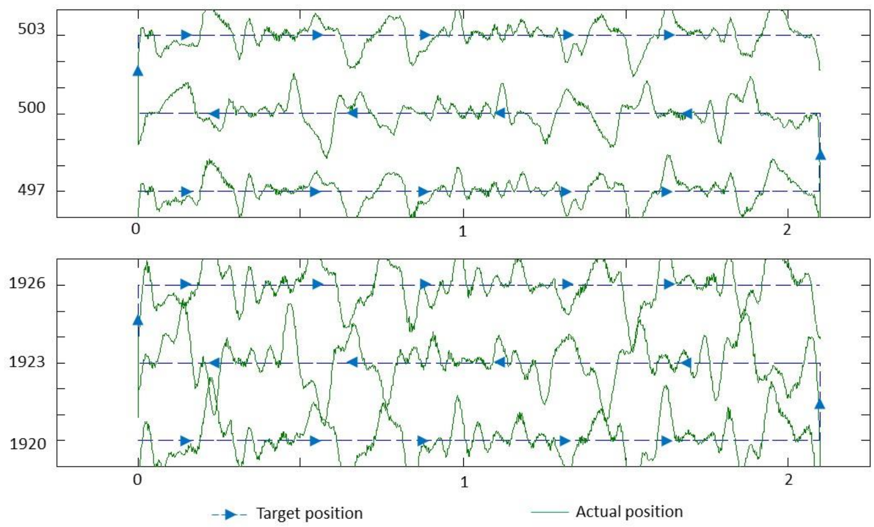

Fig. 10. Z target and actual position of the extruder tip in mm versus curvilinear coordinate in m, along three consecutive sample layers, performed without executing extrusion, at Z=0.5m (▲) and Z=1.923m (▼). Distance on the vertical axis between two sections of the actual position curve at the same curvilinear coordinate gives an image of the thickness of the layer that would have been printed.

When performing extrusion, errors pictured in Fig. 10 will result in both material being forced onto the print by the extruder piston and the tip of the extruder occasionally colliding with the print, leading to local compression force. This generates a reaction force on the CDPR as well, shifting its actual position upwards based on the limited stiffness of the cables. Together, these phenomena in the end smooth the thickness of the layers. Therefore, on the high print, at the first levels of the print (Z=0.5m), layer quality was considered good and visually homogeneous, while at Z=1.923m, layer quality was poor yet considered sufficient.

Discussion on the results

The test campaign discussed proves fruitful in experience as well as pointing out the difficulties of 3D printing on large scale and demonstrates the great potential of CDPR for AM, without the need of external sensing.

Both prints are considered good results, as they demonstrate the capacity to follow millimetric trajectories that are suitable for printing with a material wire, which measures 3mm in thickness and 11mm in width. With such trajectory following capabilities, and given past experience in CDPRs, it is also possible to carry out pick and place operations such as brick laying for construction of buildings, or for assemblies such as windows, lintels or floor elements during the building process.

Working on large scale AM with CDPR has shown new opportunities as well as limitations, to be taken in account while designing the printing pattern. A parametric periodical pattern, with curved line that does not self-intersect has proven to suit this technology best. Further research involves looking at better ways to design, simulate and plan the printing process taking into account the actual strength of the material when uncured and stressed by its own weight.

As for the CDPR, the need for robust control or higher reduction ratio to the motors in order to reach such accuracy is shown by the small vibrations generated when the platform rises. In addition, considering the accuracy that is required, dynamic gravity effect compensation as the canister is emptied proves to be necessary to achieve the print with a good global tolerance.

Future steps foresee the development of a continuous flow extruder, allowing to suppress down time from extruder loading, and print large scale elements of the size of a small building. Further research is also required on how to achieve high levels of precision with a CDPR in outdoor conditions, towards the application of on-site robotics for the construction industry.

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